The use of deep moonquakes for constraining the internal structure of the Moon

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Of the many types of seismic events detected by the Apollo seismometers, deep moonquakes were the most numerous. They were found to originate in distinct, mostly near-side clusters, at depths between approximately 700 and 1200 km (Fig. 1). Each cluster produced its own unique waveform, occurring with monthly, 7-month, and 6-year periodicity as dictated by the lunar orbit. We predict that these clusters are still active today. By taking advantage of this periodicity we can therefore project the times of their occurrence into the future (Fig. 2). Thus planned missions can rely on these events as known seismic sources.

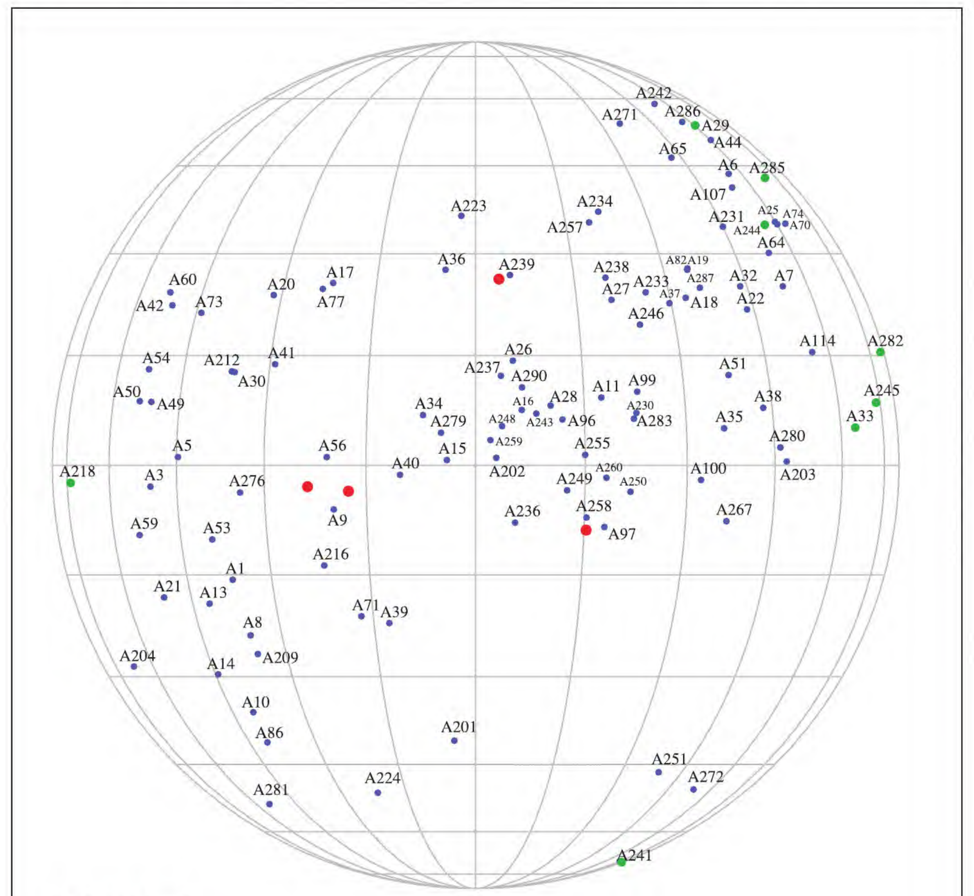

Figure 1

Near-side map of the Moon showing the locations of the Apollo seismic stations (red circles, from West, Apollo 12, 14, 15, and 16) and the epicenters of the 106 deep moonquake clusters (blue circles) with known locations [1]. Green circles mark the nearside projections of clusters located on the far-side.

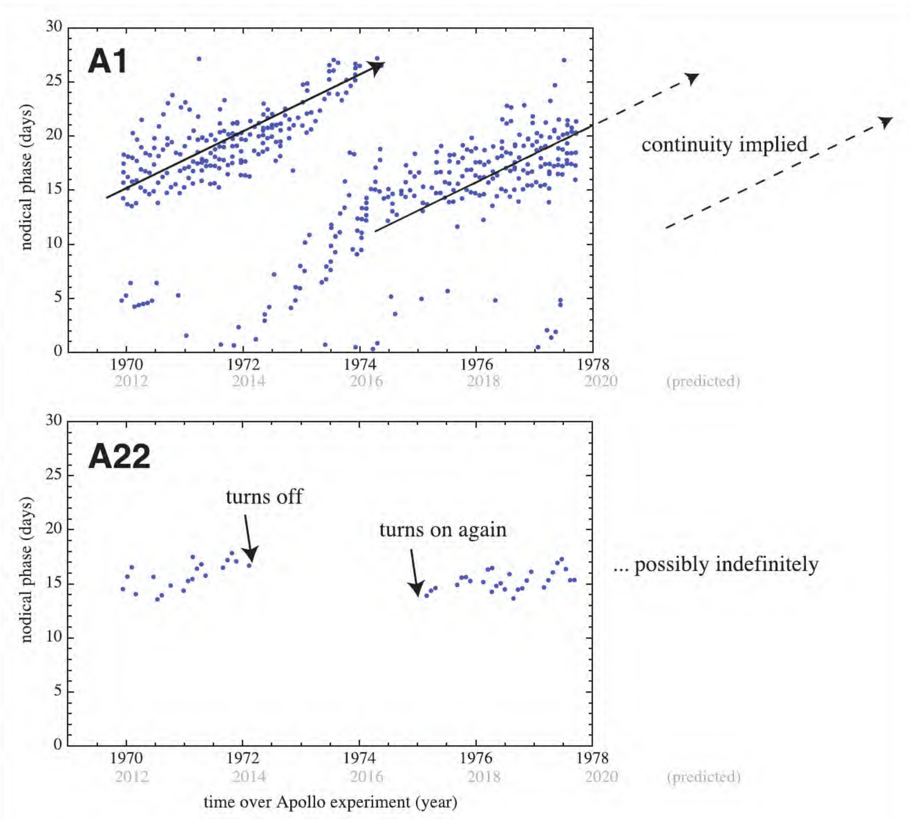

Figure 2

Nodical phase of deep moonquakes from two known clusters plotted over the length of the Apollo experiment. The phase of an event is defined as the modulus of the event time with a reference period. The near-constant phase values indicate monthly periodicity, with slight fluctuations dictated by other Earth-Moon-Sun orbit interactions. In both examples a long-term periodicity is implied by the occurrence behaviors specific to each cluster.

For most seismic methods used to determine structure, recorded events must be located. Traditional event location techniques require a minimum of four stations. Due to cost constraints, new missions may not be able to deploy that many. Fortunately, future landers will be able to operate in a virtual network with the Apollo instruments, as deep moonquake source locations are already constrained. Individual events can be linked to a known cluster using the observed S-P arrival time differences and azimuth to only two stations (Fig. 3). Events can be further identified using each cluster's unique occurrence time signature.

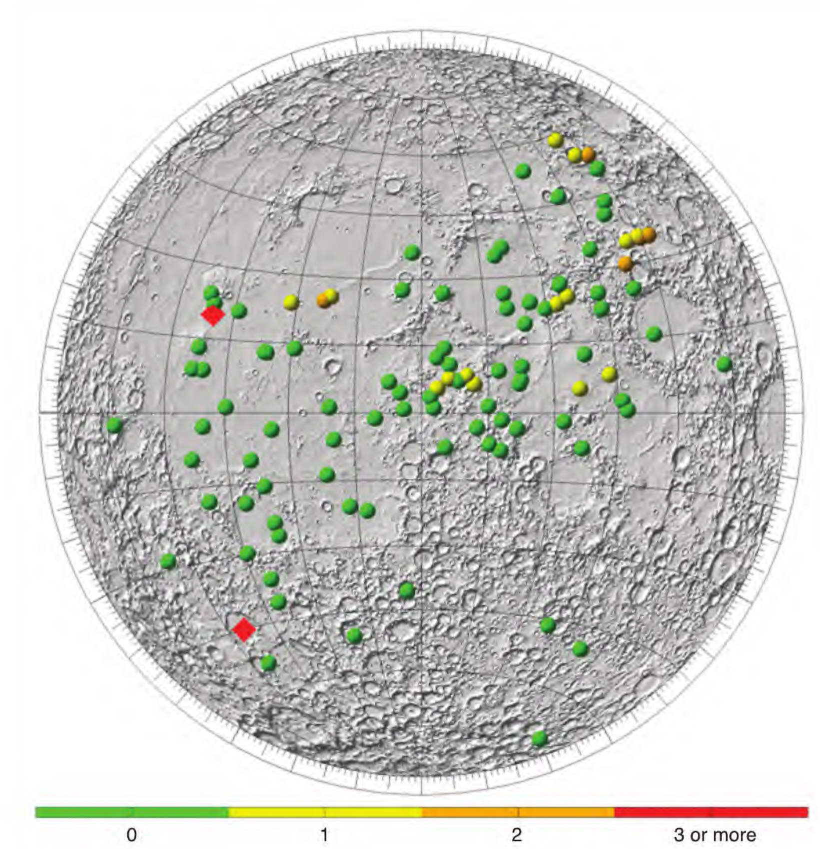

Figure 3

If we assume that, for a given event, we can measure a single-station S-P arrival time different with an accuracy of five seconds, the back azimuth to the recording station with an accuracy of ten degrees, and the time between the P arrivals at two unique stations with an accuracy of one second, we can map the clusters that can be uniquely identified using any two candidate landing site locations. In this example we have shown the results for the candidate LUNETTE [2] landing sites (red diamonds). The colorbar indicates the number of neighbors with which a given cluster can potentially be confused. A large number of clusters can be uniquely identified using information from only two recording stations. This number increases as the number of seismic stations increases.

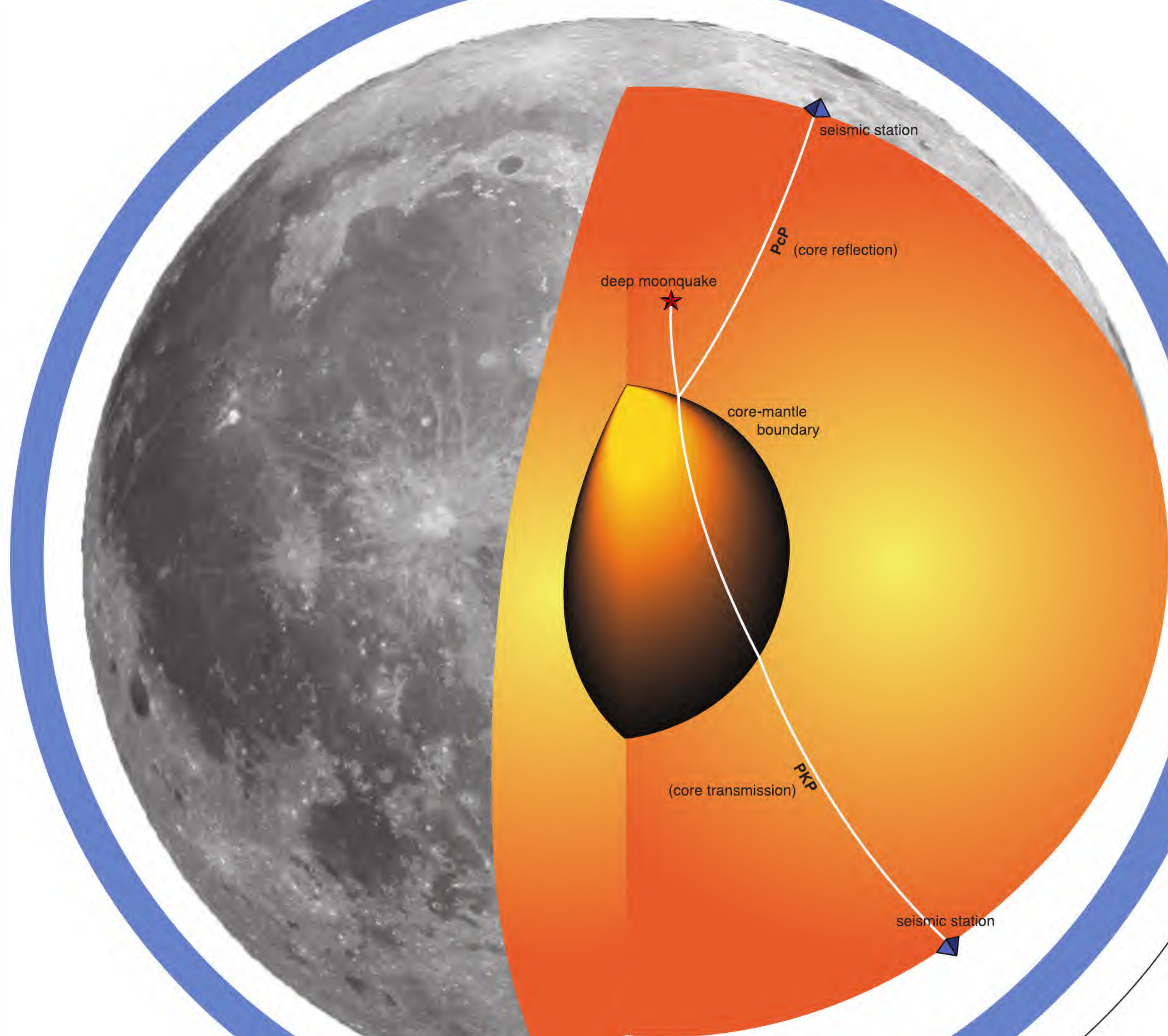

Figure 4

The installation of seismometers on the Moon's surface during the Apollo era provided a wealth of information that transformed our understanding of lunar formation and evolution. Seismic events detected by the nearside network were used to constrain the structure of the Moon's crust and mantle down to a depth of about 1000 km. However, the lack of seismic ray paths penetrating the deepest Moon prohibited definitive identification of the Moon's core. The presence of an attenuating region in the deepest interior, generally interpreted as a core, has been inferred from the paucity of farside events, as well as other indirect geophysical measurements [3]. In addition, current works have made progress in the recognition of core-reflected phases in the stacked Apollo data [4]. Such phases typically arrive in the coda of the main P and S arrivals, hampering their identification on individual seismograms.

We have devised a technique to map ideal landing sites for the detection of core-interacting phases. These include reflected phases such as PcP and ScS, and converted phases such as PKP (Fig. 4). Our method takes into account the predicted ray density, arrival amplitudes, and level of seismicity from the known distribution of deep moonquakes, and is illustrated for PKP in Figures 5 through 7. At large epicentral distances, PKP is predicted as a first arrival, and hence should be easily identifiable on future seismograms.

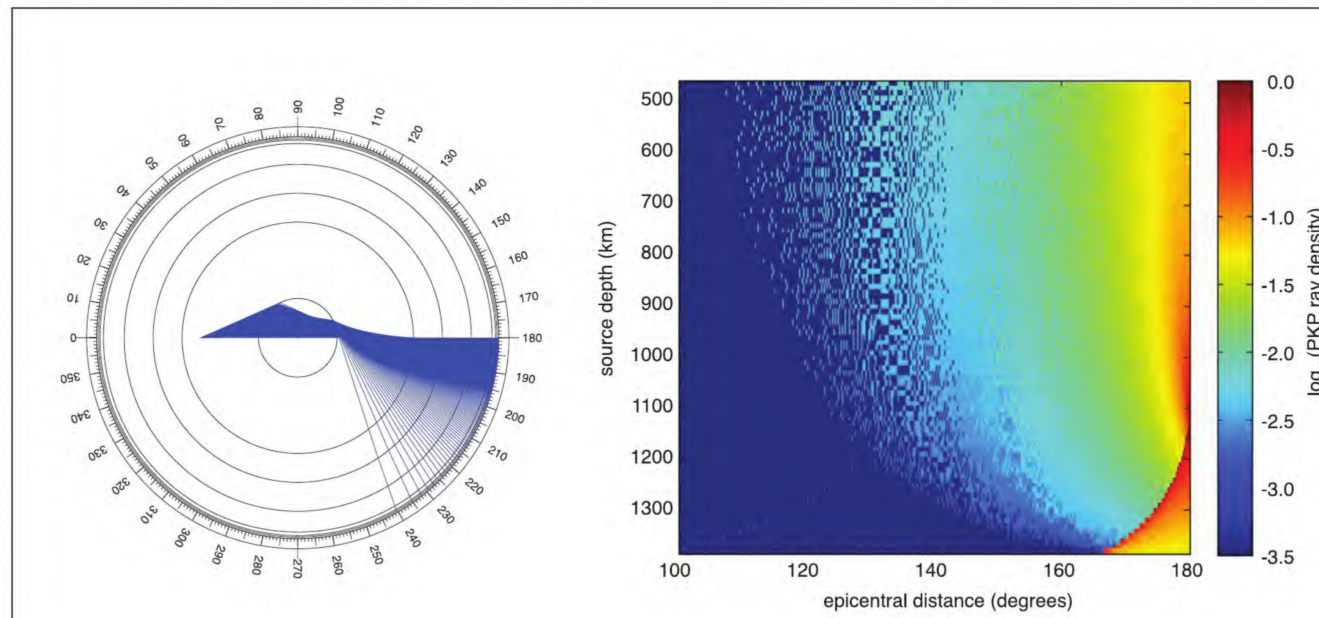

Figure 5

(left) Cross-section of the Moon showing the PKP ray fan for a source depth of 900 km. Note that the rays are more closely spaced near the antipode.

(right) PKP ray density as a function of source depth and epicentral distance. Again, note that the ray density is highest at large epicentral distance.

Both plots are based on a standard lunar velocity model [5], modified to possess a core with radius 340 km and P-wave velocity of 5.0 km/s.

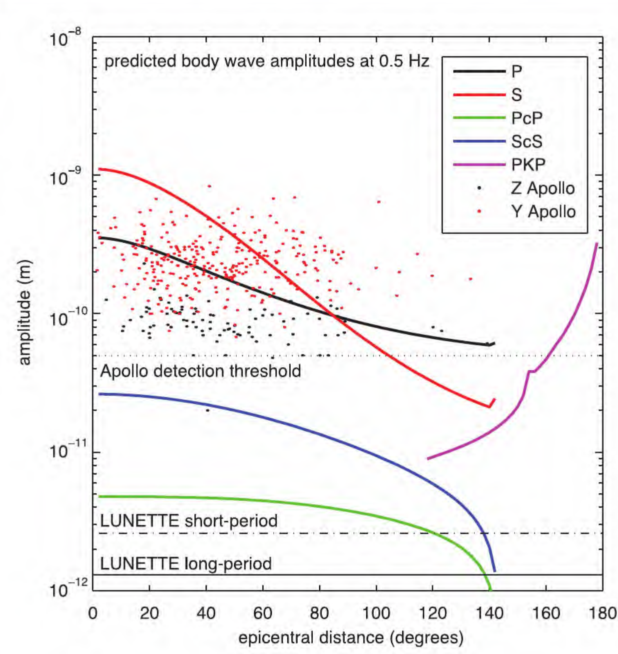

Figure 6

Predicted amplitudes for a number of seismic phases, including core-interacting phases. The dots show actual Apollo moonquake amplitudes. Note that core-reflected phases fall below the Apollo detection threshold. At large epicentral distances PKP is theoretically detectable, but such source-receiver geometries were lacking given the limited near-site extent of the Apollo network. The LUNETTE instrument detection thresholds are shown for comparison.

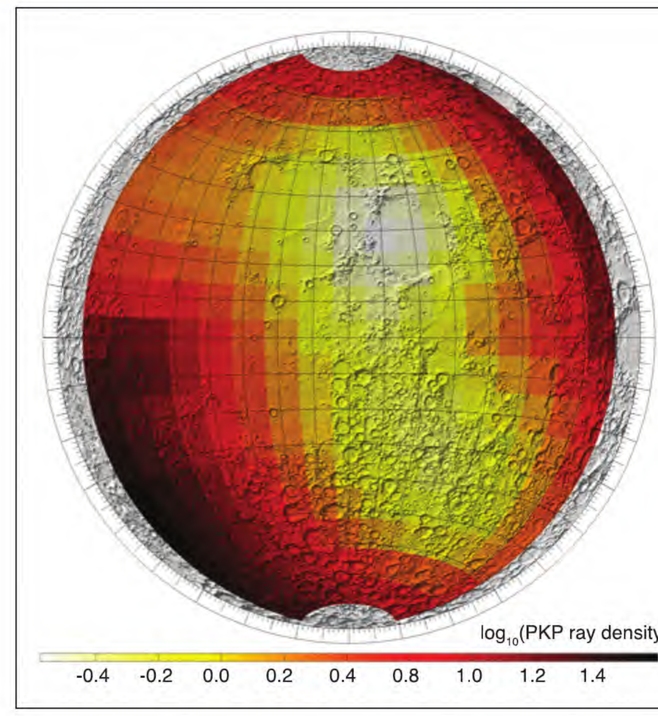

Figure 7

Nearside map of PKP ray density from the known distribution of clusters as a function of landing site coordinates, taking predicted cluster occurrence activity and arrival amplitudes into account, shown in logarithmic scale. For this particular phase, landing sites near the limb are favored, particularly in the southwestern quadrant of the Moon, where the likelihood of detecting PKP from the northeastern farside events is greatest.

Although we have focused on PKP, our landing site analysis is easily adapted to any core-interacting phase (Fig. 8). In general, the demands of a mission dictate which landing site is ideal. Core-transmitted phases give the most information about the deep lunar interior, but require more technically challenging landing sites. Core-reflected phases provide less detailed structure information, but are widely detectable.

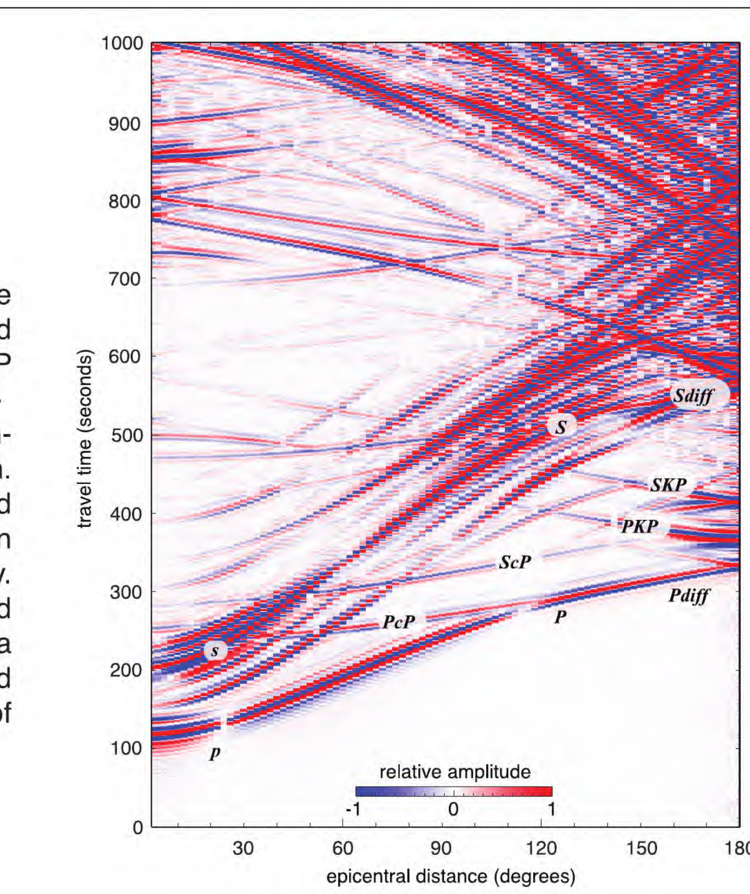

Figure 8

Travel time curves and relative arrival amplitudes predicted using a reflectivity method for P waves, S waves, and core-interacting phases, for a moonquake source depth of 900 km. The plot shows the predicted vertical component of motion with a 1 Hz dominant frequency. We modified the background reference model [5] to posses a core with a radius of 340 km and a constant P-wave velocity of 5.0 km/s.

References
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